"The Mechanism of the Electric Arc." By (Mrs.) HERTHA AYRTON. Communicated by Professor PERRY, F.R.S. Received June 5,—Read June 20, 1901.

(Abstract.)

The object of the paper is to show that, by applying the ordinary laws of resistance, of heating and cooling, and of burning to the arc, considered as a gap in a circuit furnishing its own conductor by the volatilisation of its own material, all its principal phenomena can be accounted for, without the aid of a large back E.M.F., or of a "negative resistance," or of any other unusual attribute.

The Apparent Large Back E.M.F.

It is shown how volatilisation may begin, even without the self-induction to which the starting of an arc, when a circuit is broken, is usually attributed; and it is pointed out that, when the carbons are once separated, all the material in the gap cannot retain its high temperature. The air must cool some of it into carbon *mist* or *fog*, just as the steam issuing from a kettle is cooled into water mist at a short distance from its mouth. The dissimilar action of the poles common to so many electric phenomena displays itself in the arc at this point. Instead of *both* poles volatilising the *positive* pole alone does. It is considered, therefore, that the arc consists of (1) a thin layer of carbon vapour issuing from the end of the positive carbon, (2) a bulb of carbon mist joining this to the negative carbon, and (3) a sheath of burning gases, formed by the burning of the mist, and the hot ends of the carbons, and surrounding both. The vapour appears to be indicated in images of the arc by a sort of gap between the arc and the positive carbon, the mist by a purple bulb, and the gases by a green flame.

The flame is found to be practically insulating, so that nearly the whole of the current flows through the vapour and mist alone. It is suggested that the vapour has a high specific resistance compared with that of the mist, and that it is to the great resistance of this vapour-film that the high temperature of the crater is due, and not to any large back E.M.F. of which it is the seat.

Volatilisation can only take place at the surface of contact between the vapour film and the positive carbon. When that surface is smaller than the cross-section of the end of the carbon, it must dig down into the solid carbon and make a pit. The sides of the pit, however, must be hot enough to burn away where the air reaches them, hence there is a race between the volatilisation of the centre of the carbon and the burning of its sides that determines the shape of the carbon. When

pit, hence it remains concave. When the arc is long, the burning of the sides gains over the volatilisation of the centre, and the surface of volatilisation becomes flat, or even slightly convex.

The peculiar shaping of the negative carbon is shown to be due to its tip being protected from the air by the mist, and its sides being burnt away under the double action of radiation from the vapour film and conduction from the mist, to a greater or less distance, according to the length of the arc and the cross-section of the vapour film.

It is shown that if the crater be defined as being that part of the positive carbon that is far brighter than the rest, then the crater must be larger, with the same current, the longer the arc, although the area of the volatilising surface is *constant* for a constant current.

By considering how the cross-section of the vapour film must vary with the current and the length of the arc, it is found that its resistance f, must be given by the formula

$$f = \frac{h}{A} + \frac{k + ml}{A^2},$$

where h, k, and m are constants, l is the length of the arc, and A the current. This is the same form as was found by measuring the P.D. between the positive carbon and the arc by means of an exploring carbon, and dividing the results by the corresponding currents. Hence the existence of a thin film of high-resisting vapour in contact with the crater would not only cause a large fall of potential between the positive carbon and the arc, exactly as if the crater were the seat of a large back E.M.F., but it would cause that P.D. to vary with the current and the length of the arc exactly as it has been found to vary by actual measurement.

The Apparent "Negative Resistance."

As nearly all the current flows through the vapour and mist, the surrounding flame being practically an insulator, the resistance of a solid carbon arc, apart from that of the vapour, must depend entirely on the cross-section of the mist. To see how this varies with the current, images of an arc of 2 mm. were drawn, with the purple part—the mist—very carefully defined, for currents of 4, 6, 8, 10, 12, and 14 amperes. The mean cross-section of the mist was found to increase more rapidly than the current, consequently its resistance diminishes more rapidly than the current increases. As the formula for the resistance of the vapour film shows that it too diminishes faster than the current increases, it follows that the whole resistance of the arc does the same, and that consequently the P.D. must diminish as the current increases. Hence if δV and δA be corresponding increments of

P.D. and current $\delta V/\delta A$ must be negative, although the resistance of the arc is positive.

It is found, from the above measurements of the cross-sections of the mist, that the connection between m, the resistance of the mist, and the current, is of the form,

$$m = \frac{\alpha}{A} + \frac{\beta}{A^2}.$$

If m varies directly with the length of the arc, then

$$m = \left(\frac{\alpha}{A} + \frac{\beta}{A^2}\right) l.$$

Adding this equation to (1), we get

$$f + m = r = \frac{p + ql}{A} + \frac{s + tl}{A^2}$$

for the whole resistance of the arc, which is exactly the form that was found by dividing direct measurements of the P.D. between the carbons by the corresponding currents. Hence there is no reason why this ratio should not represent the *true* resistance of the arc.

Under what circumstances $\delta V/\delta A$ measures the True Resistance of the Arc.

When the current is changed it takes some time for the vapour film to alter its area to its fullest extent, and still more time for the carbon ends to change their shapes. All the time these changes are going on the resistance of the arc, and, consequently, the P.D. between the carbons, must be altering also. Both these, therefore, depend not only on the current and the length of the arc, but also, till everything has become steady again, *i.e.*, till the arc is "normal" again, on how lately a change has been made in either. At the first instant after a change of current, before the volatilising area has had time to alter at all, δV and δA must have the same sign, just as they would if the arc were a wire, but as the volatilising surface alters, the sign of δV changes. If, therefore, a small alternating current is applied to the direct current of an arc, it will depend on the frequency of that current whether $\delta V/\delta A$ is positive or negative. When the frequency is so high that the volatilising surface never changes at all, $\delta V/\delta A$ will measure the true resistance of the arc, unless it has a back E.M.F. which varies with the alternating current.

The measurements of the true resistance of the arc made in this way by various experimenters have given very various results, because probably the frequency of the alternating currents employed has been too low not to alter the resistance of the arc. A curve is drawn showing how the value of $\delta V/\delta A$ with the same direct current and

length of arc varies with the frequency of the alternating current, and it is pointed out that even if the arc has as large a back E.M.F. as is usually supposed, the *true* resistance cannot be measured with an alternating current of lower frequency than 7000 complete alternations per second.

The exact conditions under which the *true* resistance of the arc can be measured in this way are examined, and the precautions that it is necessary to take to ensure the fulfilment of these conditions are enumerated.

The Changes introduced into the Resistance of the Arc by the Use of Cored Carbons.

A core in either or both carbons has a great effect on both the P.D. between the carbons and the *change* of P.D. that accompanies a given *change* current. It lowers the first, and makes the second more positive, *i.e.*, gives it a smaller negative or larger positive value, as the case may be. It is pointed out that this might be due to the influence of cores either on the cross-section of the arc, or on its specific resistance, or on both.

To see the effect on the cross-section, enlarged images were drawn of 2 mm. arcs with currents increasing by 2 amperes from 2 to 14 amperes, between four pairs of carbons, + solid − solid, + solid − cored, + cored − solid, + cored − cored. Two sets of images were drawn with each pair of carbons—the one immediately after a change of current, to get the "non-normal" change, and the other after the arc had become normal again. The mean cross-section of the mist was calculated in each case, and its cross-section where it touched the crater was taken to be a rough measure of the cross-section of the vapour film.

It was found that the mean cross-section of the mist with a given current was largest when both carbons were solid, less when the negative carbon alone was cored, less still when the positive alone was cored, and least when both were cored. Coring either the positive carbon alone, or both carbons, had the same effect on the cross-section of the vapour film as on that of the mist, but coring the negative alone only diminished this cross-section immediately after a change of current, but not when the arc had become normal again. Hence it was deduced that if the cores altered the *cross-sections* of the arc only they would *increase* its resistance, and, consequently, the P.D. between the carbons. As they *lower* this, however, they must do it by lowering the specific resistance of the arc more than they increase its cross-section. The vapour and mist of the core must therefore have lower specific resistances than the vapour and mist of the solid carbon.

When it is the positive carbon that is cored, all the vapour and mist

come from the *cored* carbon. When the negative, they come from the *uncored* carbon, and it is only because the metallic salts in the core have a lower temperature of volatilisation than carbon that the mist is able to volatilise these and so lower its own specific resistance.

The effect of a core in either carbon, or in both, must depend on the current, because the larger the current the more solid carbon will the volatilising surface cover, and the less therefore will the specific resistances of the mist and vapour be lowered. The way in which the core acts in each case is traced, and the alterations in the specific resistances and cross-sections due to the core are shown to bring about changes in the P.D. exactly similar to those found by actual measurements of the P.D. between the carbons. It is shown, for instance, how these changes entirely account for the fact established by Professor Ayrton* that, with a constant length of arc, while the P.D. diminishes continuously as the current increases, when both carbons are solid, it sometimes remains constant over a wide range of current, or even increases again, after having diminished, when the positive carbon is cored.

The alterations in the value of $\delta V/\delta A$ introduced by the cores are next discussed, and it is shown that the changes in the resistance of the arcs that *must* follow the observed changes in its cross-section, coupled with the alterations that must ensue from the lowering of its specific resistance, would modify $\delta V/\delta A$ just in the way that Messrs. Frith and Rodgers† found that it was modified by direct measurement. Thus all the principal phenomena of the arc, with cored and with solid carbons alike, may be attributable to such variations in the specific resistances of the materials in the gap as it has been shown *must* exist, together with the variations in the cross-sections of the arc that have been observed to take place. Hence it is superfluous to imagine either a large back E.M.F. or a "negative resistance."

* Electrical Congress at Chicago, 1893.

† "The Resistance of the Electric Arc," 'Phil. Mag.,' 1896, vol. 42, p. 407.